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Plasma Instability and Terahertz Oscillations in Resonant-Tunneling Transistors

Victor Ryzhii and Michael Shur

Abstract— **The self-excitation of plasma oscillations in a resonant-tunneling transistor structure is studied. It is demonstrated that it can give rise to the generation of transient current at frequencies in the terahertz range. The amplitudes and the frequencies of different modes of the generated oscillations are voltage-tuned.**

resonance.

I. Introduction

In this paper, we study the instability of standing plasma waves in a resonant-tunneling (RT) transistor considering the nonlinear stage of their excitation and the generation of terahertz radiation at fundamental plasma frequency and harmonics. The structure under consideration consists of an undoped quantum well sandwiched by a double-barrier RT structure from one side and thick barrier layer from another side. The QW is supplied with the side contacts. This structure is sandwiched between narrow gap doped layers serving as the collector contact and the gate, respectively. The QW plays a role of the emitter channel in which a two-dimensional (2D) electron gas is induced by biasing voltages applied between the emitter channel side contacts and both the collector contact and the gate. Similar structures were proposed and realized as working devices earlier [1], [2]. However, contrary to the normal operation of these devices, we assume that the polarity and the value of the emitter-collector voltage (V_c) are chosen to provide the RT current from the emitter channel. The emitter-gate voltage (V_g) determines the electron concentration in the QW emitter channel and, in turn, the plasma wave velocity and frequencies. [3], [4], [5], [6] The conduction band profile of the RT structure under applied voltages is shown in Fig. 1. Alternatively, we can use a structure similar to a standard high-electron-mobility transistor but with a double barrier RT structure placed into the wide gap region, which separates the channel from the gate.

II. Model

We assume that the 2D electron gas in the QW emitter channel is degenerate. The spatio-temoral variations of electron sheet concentration $\Sigma = \Sigma(t,x)$, average lateral velocity in this channel channel $u = u(t,x)$, and potential of the latter $\varphi = \varphi(t,x)$ (with respect to the QW emitter channel contacts) are described by the following set of equations:

$$\frac{\partial \Sigma}{\partial t} + \frac{\partial \Sigma u}{\partial x} = -\frac{\Sigma}{\tau_e}\Delta\left(\frac{\varepsilon_{RT}}{\Gamma}\right), \qquad (1)$$

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + \nu u = \frac{e}{m}\frac{\partial \varphi}{\partial x}, \qquad (2)$$

$$\frac{W_c + W_g}{3}\frac{\partial^2 \varphi}{\partial x^2} - \frac{\varphi}{W_c} - \frac{\varphi}{W_g} = \frac{4\pi e}{æ}(\Sigma - \Sigma_i), \qquad (3)$$

Here e and m are the electron charge and mass, τ_e^{-1} is the product of the try-to-escape frequency and the maximum transmission, ν is the electron collision frequency, W_c and W_g are the thicknesses of the RT structure and the emitter-gate barrier, Σ_i is the induced equilibrium concentration of electrons determined by their threshold voltage and the bias voltages, $\varepsilon_{RT} = \mathcal{E}_{RT} - \frac{1}{2}ea\varphi$ and Γ are the energy , and the width of RT resonance, respectively, and $a \simeq 1$ is the geometrical factor. The axis x is directed in the emitter channel plane. The RT resonance form-factor is approximated as $\Delta(z) = (1+z^2)^{-1}$. Equation (3) is a consequence of the Poisson equation in the so-called weak non-locality approximation. This equation is more general than that often used and which corresponds to the "gradual channel" approximation [7].

We shall further assume that the span of the QW emitter potential variations is not too large that nonlinearities associated with the left-hand-side terms of

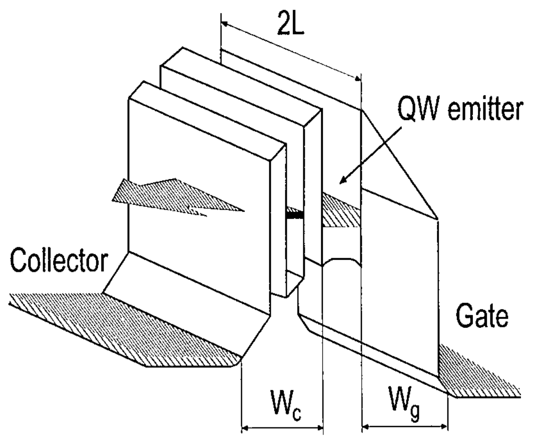

Fig. 1. Conduction band profile of the RT structure.

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Eqs. (1) and (2), i.e., hydrodynamic nonlinearities, are weak. When the width of the tunneling resonance is small, so that this resonance is sufficiently sharp, the hydrodynamic nonlinearities can be neglected in comparison to the nonlinearity caused by the voltage dependence of the RT current in the right-hand side of Eq. (1). Let us chose such a value of voltage V_c to provide $\mathcal{E}_{RT} = \Gamma/\sqrt{3}$. This voltage corresponds to negative differential conductivity of the RT structure and the maximum of its modulus. Under these assumptions, the right-hand side of Eq. (1) can be expanded in powers of φ and presented as $\frac{1}{e}[j_0 - (\sigma_{RT}\varphi + \gamma_{RT}\varphi^3)]$, where j_0 is the steady-state component of the current density, $\sigma_{RT} = -(\sqrt{3}eaj_0/4\Gamma)$, and $\gamma_{RT} = (3\sqrt{3}/64)(ea/\Gamma)^3 j_0$ is the parameter of nonlinearity of the RT structure.

The boundary conditions for the potential of emitter channel are set at the side contacts:

$$\varphi|_{x} = \pm L = 0, \tag{4}$$

where $2L$ is the channel length (see Fig. 1). In this case, searching for the emitter channel potential in the form $\varphi(t,x) = \varphi_0(x) + \sum_n \psi_n(t) \cos k_n x$, where $\varphi_0(x)$ is the steady-state component associated with the steady-state current along the channel, $k_n = \pi n/2L$ and n is the mode index ($n = 1, 2, 3, ...$), When the potential potential drop along the channel is small, i.e., $ea|\varphi_0(x)| \ll \Gamma$ (see the estimate below), the nonuniformity of the steady-state components of potential, electron concentration and current density can be neglected ($\varphi_0 \simeq 0$, $\Sigma_0 \simeq \Sigma_i = const$, and $j_0 \simeq const$), and Eqs. (1) - (3) give rise to the following equation:

$$\left[\left(\nu + \frac{d}{dt}\right)\left(\nu_n + \frac{d}{dt}\right) + k_n^2 s_n^2\right]\psi_n$$
$$= -\left(\nu + \frac{d}{dt}\right) \sum_{n',n'',n'''} \theta_n^{n'n''n'''} \psi_{n'}\psi_{n''}\psi_{n'''}, \tag{5}$$

Here $\nu_n = \nu_0/b_n$, $s_n = s_0/\sqrt{b_n}$, and $\theta_n^{n'n''n'''} = (4\pi/æ)\gamma_{RT} W \delta_n^{n'n''n'''}/b_n$, where $\nu_0 = (4\pi/æ)\sigma_{RT} W = -(\sqrt{3}\pi/æ)(eaW/\Gamma)j_0$, $s_0 = (4\pi e^2 \Sigma_0 W/æm)^{1/2}$, is the plasma wave velocity in the limit of small k_n, $b_n = 1 + (k_n^2 W_c W_g/3)$, $W = W_c W_g/(W_c + W_g)$, and $\delta_n^{n'n''n'''}$ are the coefficients determined by the overlapping integrals for different interacting plasma modes. In particular, $\delta_1^{111} = 1$ and $\theta_1^{111} = \theta_1$, where $\theta_1 = \left(\frac{3\sqrt{3}\pi}{16æ}\right)\left(\frac{ea}{\Gamma}\right)^3 \frac{W j_0}{1 + (\pi^2 W_c W_g/12L^2)}$.

III. Instability

One can show that the state with $\Sigma = \Sigma_0$ and $\varphi = 0$ can be unstable with respect to the excitation of plasma oscillations. Indeed, in the most interesting case when $k_n^2 s_n^2 + \nu\nu_n > 0$, assuming that ψ_n is small and neglecting the nonlinear term in the right-hand side of Eq. (5), one can arrive at the following formulas for the frequency of plasma oscillations (ω_n) and their growth rate (γ_n):

$$\omega_n = \left[k_n^2 s_n^2 - \frac{(\nu - \nu_n)^2}{4}\right]^{1/2}, \quad \gamma_n = -\frac{(\nu + \nu_n)}{2}. \tag{6}$$

One can see from Eqs. (6) that when the differential conductivity of the RT structure is negative and, hence, $\nu_0 < 0$, the uniform state under consideration can be unstable ($\gamma_n > 0$) with the excitation of different plasma modes having the frequencies ω_n. In this case, the criterion of instability has the form $\nu + \nu_n < 0$. The latter can be presented as

$$\frac{\nu_0}{\nu} < -1 - \frac{\pi^2 n^2}{3} \frac{W_c W_g}{L^2}. \tag{7}$$

As can be seen from this inequality, the instability occurs if the differential conductivity is negative and its modulus is sufficiently large. Inequality (7) yields the instability criterion different from that obtained previously. [8] The difference is due to the second term in the right-hand side of inequality (7) which reflects the effect of nonlocality. Such an effect imposes a restriction on the excited plasma modes if the ratio $|\nu_0|/\nu$ is fixed. Thus, in the situation under consideration the spectrum of the excited plasma oscillations is limited to relatively small mode indices n. An additional suppression of the instability of the modes with large indexes can be due to the nonideality of the 2D electron gas in the channel and due to the delay of electrons associated with the RT tunneling.

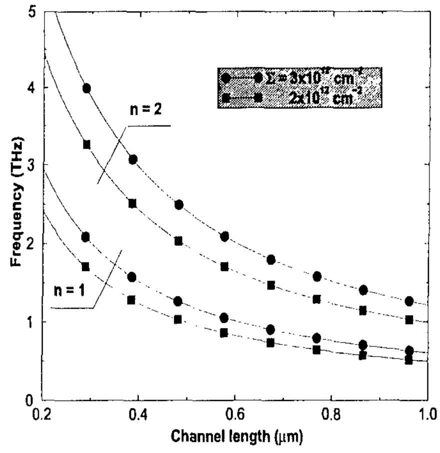

Fig. 2. Frequencies of first and second modes versus channel length for $\mu = 5 \times 10^4$ cm^2/Vs.

Figure 2 shows the frequencies of the different plasma oscillation modes as function of the channel length for different electron concentrations. for the structure with $W_c = 2 \times 10^{-6}$ cm, The structural

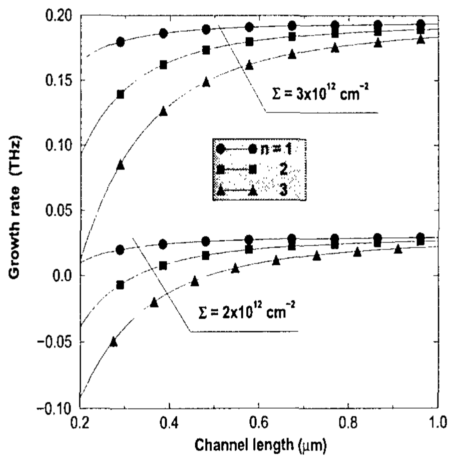

Fig. 3. Growth rate of different plasma modes versus channel length at different electron concentrations for $\mu = 5 \times 10^4$ cm^2/Vs.

parameters used for this and subsequent figures are as follows: $W_g = 4 \times 10^{-6}$ cm, $\Gamma = 7.5$ meV, and $\tau_e = 17.5$ ps, One can see that at reasonable device sizes and electron concentrations, the plasma frequencies fall into the terahertz range. Figure 3 shows the dependencies of the plasma oscillations growth rate versus the channel length, As can be seen from Fig. 3, the increase in the electron concentration leads to a significant rise of the growth rate of plasma oscillations and the marked increase of the range where such a growth occurs. The use of the channel with higher electron mobility favors the instability conditions.

IV. Nonlinear oscillations

We shall search for the solution of Eq. (5) in the form $\psi_n(t) = A_n(t)\cos[\omega_n t - \alpha_n(t)]$, where amplitudes $A_n(t)$ and phases $\alpha_n(t)$ are relatively slowly varying functions of time. Further we shall assume that only the fundamental mode ($n = 1$) of the plasma oscillations has a positive increment. Substituting ψ_n into Eq. (5) and averaging over the period of the plasma oscillation, near the instability threshold, where $|\nu + \nu_1|$ is small, one can obtain the following equation for the amplitude of fundamental mode ($n = 1$) of plasma oscillations (compare with [9]):

$$\frac{dA_1}{dt} + \frac{(\nu + \nu_1)}{2} A_1 = -\frac{3}{8}\theta_1 A_1^3, \tag{8}$$

$$\frac{d\alpha_1}{dt} = \frac{(\nu + \nu_1)^2}{4\omega_1} + \frac{3}{16}\frac{(\nu_1 - \nu)\theta_1}{\omega_1} A_1^2, \tag{9}$$

Deriving Eqs. (8) and (9), we neglected the nonlinear effect of higher modes ($n > 1$) because such modes are assumed to be stable in the linear approximation. However, the excitation of the fundamental mode can result in the forced excitation of the stable modes. Nevertheless, when $|\nu_1|$ barely exceeds ν, one can assume that the amplitudes of higher modes are rather small.

As follows from Eq. (9), the temporal evolution of the amplitude of the oscillations is given by

$$A_1 \simeq A_1^0 \frac{\exp(-\frac{1}{2}(\nu + \nu_1)t)}{[1 + (A_1^0/A_1^\infty)^2 \exp(-(\nu + \nu_1)t)]^{1/2}}, \tag{10}$$

where A_1^0 is the initial amplitude (its fluctuational value) and A_1^∞ is the final steady-state amplitude: $A_1^\infty = [-4(\nu + \nu_1)/3\theta_1]^{1/2}$. This state is stable, because for its small perturbations Eq. (9) yields $\gamma_1 = \nu + \nu_1 < 0$. Near the stable state, the oscillation phase slowly varies. This corresponds to the following nonlinear correction of the plasma frequency: $\Delta\omega_1/\omega_1 \simeq \nu(\nu + \nu_1)/\omega_1^2$.

Using the obtained amplitude of oscillations of the potential in the QW emitter channel one can arrive at the following expressions for the amplitudes of the first ($\delta J_1 \propto A_1/\Gamma$) and third ($\delta J_3 \propto A_1^3/\Gamma^3$) harmonics of the electron current from the QW emitter channel to the collector contact caused by the fundamental plasma harmonic:

$$\frac{\delta J_1}{J_0} \propto \left(1 - \frac{J_{th}}{J_0}\right)^{1/2}, \qquad \frac{\delta J_3}{J_0} \propto \left(1 - \frac{J_{th}}{J_0}\right)^{3/2} \tag{11}$$

where $J_{th} = \left(\frac{2æ}{\sqrt{3}\pi}\right)\left(\frac{L}{W}\right)\left(\frac{\Gamma\nu}{ea}\right)$ and $J_0 = 2Lj_0$ is the dc emitter-collector current. The amplitudes of ac electron current can also be expressed via the electron concentration in the QW emitter channel: $\delta J_1/J_0 \propto [1 - (\Sigma_{th}/\Sigma_0)]^{1/2}$ and $\delta J_3/J_0 \propto [1 - (\Sigma_{th}/\Sigma_0)]^{3/2}$, where $\Sigma_{th} = \frac{2æ}{\sqrt{3}\pi}\frac{\Gamma\nu\tau_e}{e^2 aW}$. Going back to Eq. (5), one can find that the coupling between the fundamental (unstable) and higher (stable) modes should not result in a marked excitation of the latters if the amplitude of fundamental mode is not too large, i.e., near its excitation threshold: $(J_0 - J_{th}) < J_{th}$ or $(\Sigma_0 - \Sigma_{th}) < \Sigma_{th}$ Figure 4 shows the relative amplitude $\delta J_1/J_0$ of the established current oscillations at the fundamental frequency as a function of the electron concentration in the QW emitter channel for different electron mobilities in the latter. Due to the dependence of the induced electron concentration in the QW emitter channel on the bias voltages, particularly, the emitter-gate voltage, $\Sigma_0 \propto V_g - V_{th}$, (where V_{th} is the threshold voltage), the amplitude of ac electron current can be effectively controlled by this voltage. The emitter-gate voltage can also tune the frequency of the excited current oscillations.

Using Eqs. (1) - (3), one can estimate the potential drop along the channel as $max\, e|\varphi_0| \sim J_0(\nu mL/e\Sigma_0)$. Accounting for this estimate, one can find that conditions $max\, ea|\varphi_0(x)| \ll \Gamma$ (weakness of the steady-state potential nonuniformity) and $J_0 > J_{th}$ (see relationships (11)) do not contradict to each other if

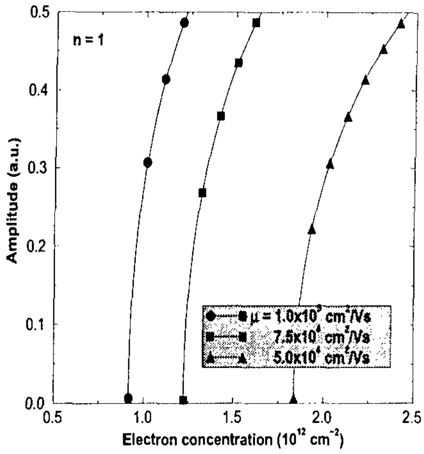

Fig. 4. Amplitude of oscillations versus electron concentration in the channel in structures with different electron mobilities and $2L = 0.3$ μm.

$\nu \ll s/L \sim \omega_1$. This inequality corresponds to sufficiently high electron mobility and concentration in the channel and sufficiently small length of the latter. It is typical for different devices utilizing the plasma waves (see, for example, [4], [5], [6]). Consequently, the electron drift should not lead to a marked change in the instability conditions. However, at a large potential drop along the channel, one may expect a marked change in the RT transistor behavior due to a combination of the considered mechanism and the instability mechanisms studied previously.

V. Conclusions

Using an analytical model, we studied the self-excitation of terahertz current oscillations and their nonlinear stage in a RT transistor structure associated with the plasma instability in the QW emitter channel. The criteria of the instability were found and the oscillations frequency and amplitude were calculated as functions of the structural parameters and biasing voltage.

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